Supplementary Material: Environmental Comparison of Different Mechanical–Biological Treatment Plants by Combining Life Cycle Assessment and Material Flow Analysis

Giovanni Gadaleta , Sabino De Gisi, Francesco Todaro and Michele Notarnicola

Table S1: Environmental impact categories and normalization factors for European Inhabitants Equivalent [30].

Impact category	Normalization factor	Unit
Global Warming	1.29E+04	kg CO_2-Eq/y*capita
Acid Rain	7.15E+01	kg SO_2-Eq/y*capita
Eutroph'n	3.34E+01	kg PO_4-Eq/y*capita
Aqua Ecotox	1.32E+03	kg 1,4-DCB-Eq/y*capita
Health	1.98E+03	kg 1,4-DCB-Eq/y*capita
Resources	3.86E+01	kg Sb-Eq/y*capita

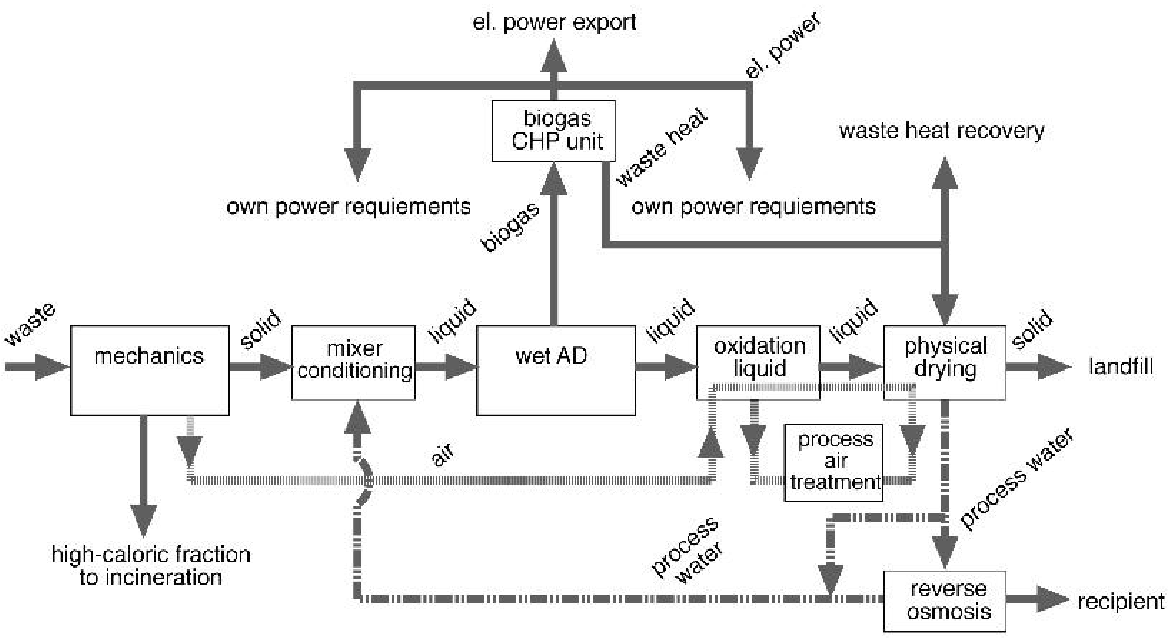

Figure S1: Scheme of the Haase MBT plant.

At the first step of an MBT process the input material is divided into separate substance flows by a number of screening and separating procedures. At the beginning of the wet AD process we have a liquid suspension with a dry matter content of about 10 to 15 percent. Subsequent separation of light-density material and medium solids produces a substance suitable for anaerobic digestion. Digestion of biogenous matter in the anaerobic stage of treatment of an AD plant does, in principle, work in the same way as inside of a landfill body – but the process needs less time. After the AD & oxidation process the suspension is separated into solid and liquid matter. While the liquid is forwarded to the mixer the solids will first be dried, then landfilled.

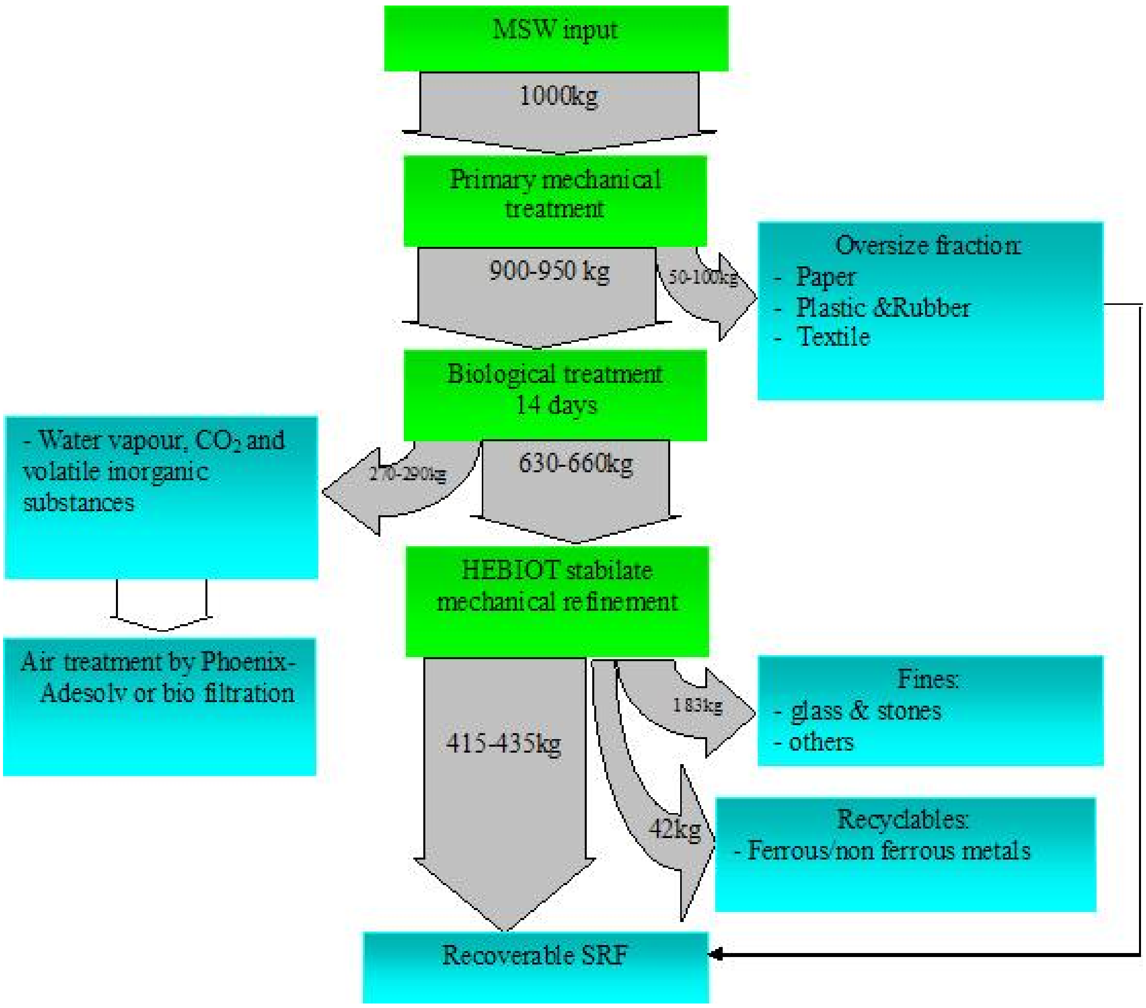

Figure S2. Scheme of the Entsorga MBT plant.

The technology is based upon the 'hall' type MBT process, using remotely controlled overhead cranes to move all materials within the hall effectively removing any need for personnel to become involved in the process except for maintenance. This greatly limits the exposure of personnel to health and safety issues compared to tunnel systems (vehicle movement and foul air) providing a cleaner working environment as all emissions are contained within the building (held at negative pressure) and cleaned by a unique ceramic/catalytic the air filtration system.

Residual Municipal Solid Waste (MSW) is deposited directly into the reception pit in the building from refuse trucks. Access is through opening roller shutter doors and air is continuously drawn into the building to avoid escape of odour.

The waste is moved from the reception pit by the overhead crane into a fast rotary drum. The drum opens the waste bags and removes any oversize material. This is typically plastic film and cardboard but also rogue objects, such as large pieces of metal can be removed. The removal of the plastic film and card means that these can be recycled or returned to the refinement stage as they are effectively inert in terms of the bio-stabilisation process. This also gives the facility additional capacity for bio-stabilisation of the organic fraction compared to systems that use shredding as pre-treatment.

Once the waste has passed through the rotary drum it is moved by the crane into the bio-stabilisation section where it is placed in windrows across the width of the plant. The floor of the plant has specially engineered ventilation slots that are used for drawing air through the waste to control the rate of biological activity and temperature. A particular innovation of the plant is its ability to use existing hot air from active waste re-circulating this into the waste that has just arrived at the plant. This means that the biological activity in the waste begins rapidly and improves the overall effectiveness of the plant. Additionally, the ability to supply hot air to the waste means that temperature gradients can be reduced and the possibility of fly infestation greatly reduced.

After 10 to 14 days, depending upon moisture content the waste is dried, sanitised and stabilised and can be moved by the cranes to the refinement section.

The refinement process removes further recyclates, particularly metals, and provides options for the preparation of solid recovered fuels (SRF) or landfill. As the waste has been dried conventional shredders, screens and air classifiers are easily used to produce a homogenous feedstock of the appropriate particle size for cement manufacture or other thermal processes. The fuel is prepared to the CEN 343 standard.

Phoenix System:

When a woodchip biofilter is not used to control odour emissions, a ceramic filter and catalytic oxidation control unit (Phoenix Adesolv) is used. The principle of the system is that exhaust gases are passed through a ceramic filter to remove organic molecules (including VOCs) that adsorb onto the ceramic matrix. When this is saturated desorption/regeneration of the bed takes place, by heating to 80oC, stripping the volatile organic compounds from the bed. The concentrated organic compounds removed from the filter are then passed over a catalyst heated to 140oC at which stage the oxidation becomes self supporting oxidising the compounds to water and CO_2.

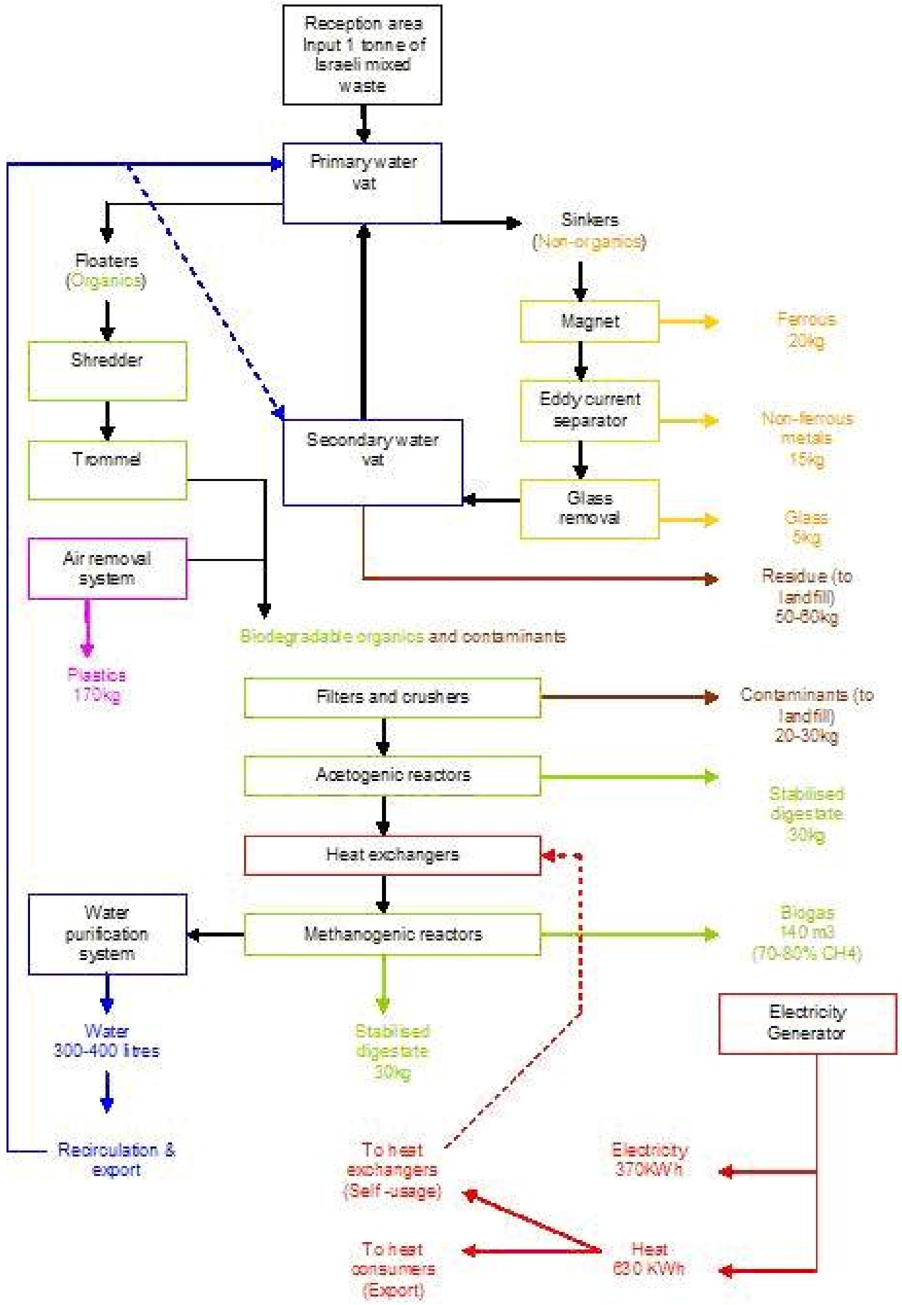

Figure S3. Scheme of the ArrowBio MBT plant.

The ArrowBio Process integrates an innovative, proven, liquid-based separation technology and high-rate anaerobic digestion - eliminating any need for prior separation or classification of mixed waste streams. The following types of wastes can be treated as-received: Municipal Solid Waste (MSW); unsorted industrial waste from the paper (including recycled paper) and food processing industries;

manures and agricultural residues; slaughterhouse wastes; sludge from sewage and water treatment plants; industrial settling tank sludge; and, yard waste/garden trash with or without other household discards.

Of these wastes, the most universal, and probably the most problematic, is unsorted MSW. It consists of a myriad of discards from households, businesses, and institutions managed in common. Thus MSW is extremely heterogeneous, seasonally variable, and differing in composition even among different collection routes within a given municipality. The organic and inorganic fractions pose very dissimilar problems, yet are received as a mixture in a single waste stream. As a severe test of the ArrowBio Process, a realistic scale facility is in operation at the town of Hadera, Israel. Real unsorted MSW is received from the city and processed smoothly. The fundamental advantage of the ArrowBio process is two-fold. First, the MSW (or other waste stream) is processed directly as tipped from the collection truck. In the primary stage, organic and inorganic materials are separated through a unique, liquid-based, technology, involving gravitational settling, screening, and hydro-mechanical shredding of organic solids. Whereas ordinary separation schemes suffer from the wetness, or excessive dryness, of MSW, the ArrowBio process uses liquids to great effect. The first stage end products are clean recyclables such as glass, metals, and plastic. Items such as batteries are removed gently, without breakage, thereby avoiding leakage of potentially toxic materials. Yet another, intermediary, product is an organic stream now ready for the next, biological, stage. The first stage thus performs two functions, separation and preparation, without additional machinery or effort. That is, in addition to removing inorganic and other non-biodegradable materials, the liquid-based separation simultaneously conditions the organic material for rapid biological action. This is accomplished by bringing the organic matter into solution or fine suspension (slurry). The solution/suspension is very rich, with a chemical oxygen demand (COD) in the tens of thousands of milligrams per litre. This supports the high-rate transformation of the organic wastes to methane (biogas) by naturally occurring microbial communities, in two highly controlled sequential reactors. Biogas production far exceeds in-house energy needs. Excess biomass, discharged from the second reactor, is thoroughly stabilised and usable directly as an organic soil amendment (compost), or may be upgraded to a value-added product. Excess biologically generated water is either removed from the system (COD in the tens of milligrams per liter) or sent as makeup liquid to the up-front separation stage. Thus, with respect to energy and water, the system is autonomous. Since it is consumed in producing energy for in-house use and/or export, emission of methane (potent greenhouse gas) to the atmosphere is entirely prevented. Significant regional differences in MSW composition are noteworthy. In the Middle East and Asia, biodegradable organic matter may comprise 60 to 90% of the waste stream, with the remainder as biologically inert, mostly inorganic, materials. In contrast, European and North American MSW generally contains only 30 to 50% organics. Regardless of organic/inorganic proportion, unsorted MSWs are treatable by the ArrowBio process. The ArrowBio process effortlessly accommodates the increasing tendency, mandated by national or local laws and regulations, to require source-separation of recyclable materials at the household, business, or institution of origin. Resultant shifts in MSW composition pose no problem in the process cycle. Rather, a given facility's capacity is effectively increased by this tendency. Moreover, perfect compliance with such mandates is neither expected nor achievable. Anyway, the function of conditioning the organics for high-rate methane production is indispensable.

Pre-Treatment and Preparation of the Waste

The waste is delivered by trucks into the preparation building. This building is equipped with exhaust fans and Bio-Filters, which assure that no smells escape into the environment. The waste is emptied directly into a reception chute and passed through a bag opening unit and a wet shredder. Water, essential for the shredding process, is re-circulated within the plant and no additional water needs to be added. From there the waste is transferred directly into the dissolving tank. Water is added and by imposing high shearing forces, the organic material is disintegrated down to fibre size, forming slurry so it is separated from any inert material. Heavy components like broken glass, batteries, stones, metal parts etc. sink to the bottom and are separated from the slurry via a special discharge chamber.

1st Stage Acidogenic Fermentation

The organic slurry is pumped into the first Bio-Reactor or fermentation tank for facultative anaerobic digestion of the organic phase. Naturally occurring microorganisms start the fermentation process and transform the complex organic material into simpler compounds such as organics and fatty acids. Maintaining correct pH and organic material concentrations in the reactor, together with proper liquor circulation and hydraulic retention time controls the process. This stage is a continuous process where fresh slurry is fed into the 1st reactor and fermented liquid is drawn off simultaneously and transferred to the 2nd stage.

2nd Stage Anaerobic Methanogenic Fermentation

The liquids leaving the 1st stage reactor are rich in organic material in the form of various organic acids. These liquids are being heated to ~40°C and pumped into the second Bio-Reactor for anaerobic degradation of the organic materials and the generation of biogas. Here too, naturally occurring micro organisms perform the degradation process and transform the organic material into biogas (~ 70% CH_4:30% CO_2) and biomass. This process is controlled by maintaining correct pH and organic material concentration in the reactor, together with proper solids concentration in the liquor and correct circulation and hydraulic retention time. This stage is also a continuous process where liquids from the 1st reactor are fed to the 2nd reactor and effluents are removed from the 2nd reactor. These effluents are being recycled within the system in order to maintain proper solids levels in the 1st reactor and for the initial stages of shredding of the incoming waste and the separation of inert material. Basically, no fresh water is added to the system. The biogas, which is formed in the 2nd reactor, is being collected at the upper part of the reactor by means of a specially designed built-in compartment. This gas is re-circulated by a compressor and re-injected into the 2nd reactor close to its bottom, thus assuring a permanent agitation without mechanical devices. During routine operation, the biogas is also routed out of the system directly to energy generating units as steam boilers or electrical generators. The biogas can also be stored in simple inflating buffer tanks.

Treatment of Final Products

The biological sludge formed in the 1st and 2nd reactors is drawn off at pre-set periods, dictated by the process control. This sludge contains many plant nutrients such as ammonia and phosphorus in a readily available form for the plants. This fraction, called ArrowBio compost, can be dewatered rather simply and sold as a high value soil-conditioning agent. Further processing such as pelletisation of this product will increase the market potential and value of the ArrowBio compost. The long solid retention time in the 1st and 2nd reactors ensures a fully stabilised product which do not deplete the soil of nutrients due to intrinsic microbial activity and also is free of all pathogenic germs, bacteria, weed seeds, etc. The biogas generated in the 2nd stage reactor is transported into a gas storage tank via filters, which remove excess humidity, and trace pollutants such as naturally formed H_2S. The biogas is then used as a fuel for water heating, steam generation or electricity generation. The liquid from the dewatering process of the ArrowBio compost is partly reused for shredding and dissolving the incoming waste. Excess water is stored in a separate tank and is discharged directly into the public sewage system or into a simple biological treatment plant.

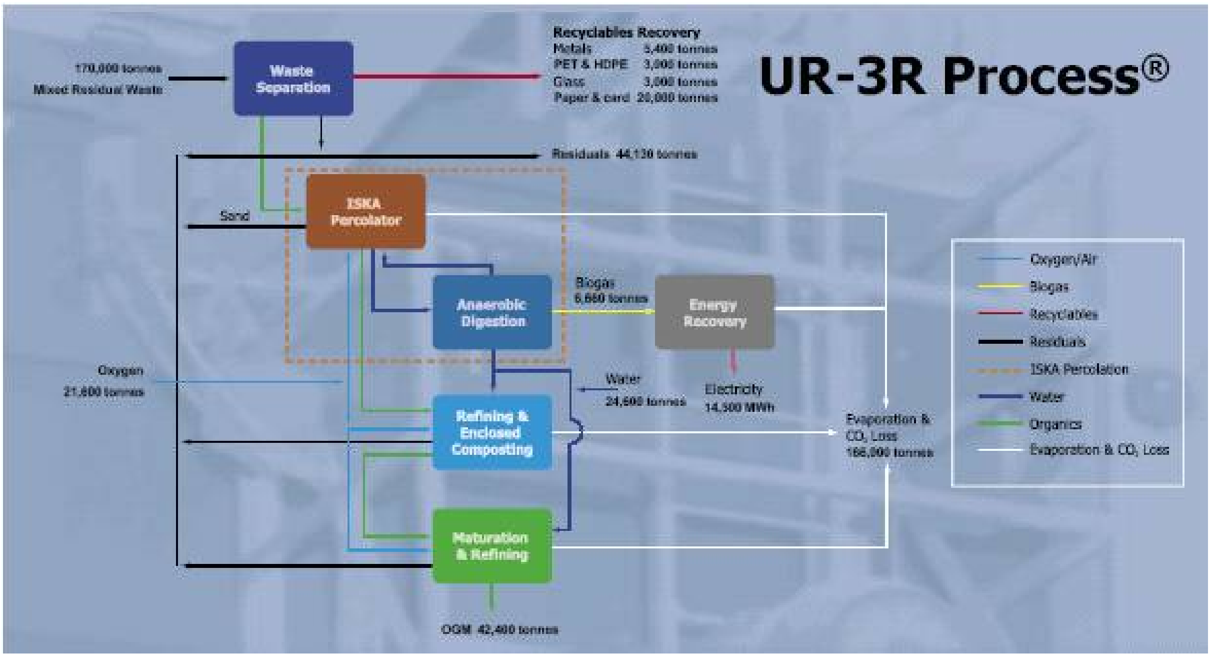

Figure S4. Scheme of the Global Renewables MBT plant.

The UR-3R Facility receives and processes municipal solid waste (MSW), which includes collected household, commercial and green waste. The facility integrates unit process technologies in: waste stream separation; ISKA® Percolation; SCT Composting and refining; and, energy recovery. Each unit process is proven and currently in commercial operation around the world. The Eastern Creek UR-3R Facility in Sydney is the first to fully integrate these leading technologies to provide a total solution for waste management. There are 11 stages in the process:

The Receivals Area employs fast acting doors and air curtains as a means of reducing the potential for fugitive emissions. Depending on local requirements the receival systems are either designed for flow through of traffic, where the doors are open only long enough for trucks to pass through, with airlocks that the trucks can reverse into, or traffic light controlled. Whilst the buildings are under negative pressure, and the doors are open only for short durations, as an additional precaution against the escape of odour or litter, air curtains are installed on all doors with vehicular traffic, operating whenever the doors are open. The waste is then inspected to ensure compliance with material classified as catering waste that the plant is licensed to treat for ABPR purposes. Wheels of trucks are washed before they leave site to comply with ABPR requirements.

The Pre-sort Station consists of a feed system (comprising feed hopper and belt feeder) which regulates the flow of material, and a "sorting" conveyor. Waste is fed by front-end loader into the pre-sort feeder and bulky materials are removed. Both the feeder and the sorting conveyor are variable speed to allow control of feed rate in order that a shallow bed depth of material is achieved on the sorting belt, to allow hand-sorting personnel to visually identify and remove hazardous and incompatible material.

The Separation and Sorting stages start with a 'Bag Opener' which mechanically opens plastic bags, in order that the contents may be discharged in subsequent processing stages. A Scalping Trommel undertakes the first stage of separation and separates the material into two size fractionated streams, oversize and undersize. The Organic Removal Trommel treats the undersize fraction from the scalping trommel and fractionates the material into two sizes. The screens are enclosed and have an air extraction point for connection to the plant extraction system. Windsifters are located at selected conveyor transfers where the falling material stream is opposed by an air stream. An air curtain, generated by a combination of the windsifter blower and suction fans, removes the suspended light materials such as plastic film and dry loose paper from the falling waste stream. A sorting cabin is utilised for manual sorting of the recyclable materials from the material discharged as oversize from the Scalping Trommel and Organic Recovery Trommel. The sorting belt operates at slow speed and is fitted with a variable speed drive to allow selection of the most appropriate operating speed and hence bed depth. Ferrous metals are separated from the waste by overband electromagnets and are often contaminated by adhering organic matter. In addition, many of the steel cans retain part of their original contents, whilst others will be contained inside plastic bags (which were too small to be opened in the bag opener at the head of the circuit). The metals cleaning circuit opens these bags and removes the plastic, residual contents and as many other non-metallic contaminants as possible, to give a relatively clean product suitable for sale. The system is a dry process and consists of a trommel screen followed by electromagnets to recover the metal. The trommels have sufficient residence time so that the tumbling action of the sharp metal objects will degrade the plastic bags and dislodge any adhering organic material. Whilst the metals are retained within the trommel, the liberated fine organic material is discharged through the screen to minimise the potential for recontamination of the metals. Electro-magnets are utilised on the trommel undersize and oversize streams to collect the ferrous metals, whilst rejecting the organic matter and other non-magnetic contaminants. Non-ferrous metals are separated from the waste by the use of eddy current non-ferrous separators. Compaction presses and transport containers are installed for waste materials of low density, in order to allow trucks to be loaded to their rated capacity.

The unrecovered materials from sorting are then fed to Residuals Shredders which consist of slow-running, high torque, single or dual shaft roll crushers. The Organic Scavenging Trommel treats the residual oversize from the scalping trommel after recyclables have been recovered and following shredding. The trommel splits material between two size fractions with the fines going to composting and the oversize going to landfill. A Baling Press is utilised for the compaction of the separated Recyclable materials. The press includes buffer storage for the incoming material and for the bales produced. The unit incorporates a wire-tying system to ensure the integrity of the completed bales during transport. The produced bales are removed from the load-out table by forklift for transport and stacking in the storage area.

The undersize from the trommel screen is fed into one end of an ISKA® Percolator where it is irrigated and aerated. It is also intermittently agitated to move it through the Percolator over a two-day period. The temperature within the Percolators is maintained by preheating the irrigation water. Bacterial hydrolysis reactions assist with washing out soluble organics and odour causing species, so that the immediate odour production potential of the material is greatly reduced by the time it leaves the Percolator. Excess water is drained from the bottom of the Percolators through a grate system carrying with it some of the sand and fine glass. The solids and entrained liquid are fed to a filter press after Percolation, to recover semi-dry solids that can be screened to further upgrade the organics. The liquid from the filter press along with the water recovered directly from the Percolators provide the feed to liquid phase anaerobic digestion.

The Anaerobic Digestion of Liquid Percolate Stream comprises of three stages:

- Anaerobic digestion of volatile matter in the liquid stream from the ISKA® Percolators;
- Recovery and treatment of biogas from the Digester to produce electricity; and
- Recovery and utilisation of treated water from the Digester.

The screened percolate is pumped from the digester feed tank to the digesters. Digester feed is metered into each digester on a frequent basis. Each digester is equipped with a dedicated circulating pump to constantly recirculate the digester contents through an individual digester heat exchanger. During normal operation, the percolation water is constantly mixed into the digester feed stream prior to passing through the heat exchangers, and the digester feed liquid is heated before re-distribution back to the digester. The proportions of circulation fluid and the added percolate can be adjusted or changed in response to the material composition via a variable speed controller. A separate pump is also installed on each digester to transfer the digester liquor back to the percolators. Using the circulating water suction manifold, the transfer pump on each digester will pump liquor back to the percolator distribution manifolds. This pump is also used to pump digester outlet liquor into the water denitrifiers. Prior to distribution to the percolator manifold, digested liquor will be heated. Excess water from digestion is used for compost moisture maintenance. Each digester vessel includes an inert biological support for retention of biomass. The biomass support or filter bed is filled with polypropylene packing VPP-VSD. Biomass adheres to the surface of the packing, or forms bridging flocs providing a relatively high biological loading in minimal volume. The fixed nature of the biomass allows greater variations in feed capacity when compared with alternative digester configurations, by virtue of a stabilised biomass population. The digesting liquor is circulated through the media and organic degradation occurs with the biomass supported on the media. The COD is converted to biogas that is collected at the apex of the digester and passed on to the biogas processing section.

The digester is also equipped with a bottom rake and screw conveyor for desludging/desanding the digester floor. The sludge discharge takes place as required and is manually operated (normally once a week for a maximum of 60 minutes). The sludge is pumped into a tanker for disposal onto the compost or to landfill. The discharge of the sludge is monitored by an operator and is terminated manually when the solids loading is reduced.

Prior to Electricity and Heat Recovery From Gas Engine Combustion of the Biogas, the gas will be scrubbed to H_2S levels, at which the biogas can be burnt safely in gas engines with minimal operational problems. The biogas is passed through a dedicated oxidative desulphurisation column before being used as gas engine fuel. The H_2S is removed in a single stage vertical counter flow, packed bed, fibreglass scrubber column through which ethylene diamine tetra-acetic acid (EDTA) solution is circulated. The spent solution is pumped through a stand-alone catalytic reactor to enhance absorption efficiency by liquid phase oxidation of pollutants. Desulphurised biogas is stored in an inflatable, double-skinned, membrane storage vessel. A gas flare is provided to allow the biogas to be burnt during emergency shutdowns or maintenance periods. During normal operation of the power general facility, biogas is withdrawn from the storage vessel and compressed in individual blowers to supply the packaged gas-fired process water heater, the bio filter air heater and the generator engines. Two biogas engines with integral transformers are installed to generate over two thirds of the electricity requirements of the MBT facilities. Waste heat is also recovered from the engines for process heating to increase the energy utilisation efficiency. The biogas engines are standard spark-induced diesel engine generator sets adapted to biogas operation.

The First ABPR Barrier Treatment of Solids From Percolation is carried out with a conveyor which transfers the solids from the filter press after percolation to the first stage of the SCT Biomax-G® automated composting system. The purpose of the first stage is to satisfy the requirements of the first barrier in a composting process to meet SVS ABPR requirements. During the week that the material spends in the first section of the SCT process the target criterion is to achieve a temperature of at least 60°C for two days. In practice once this temperature is achieved it is maintained for the rest of the time as temperature control is achieved by varying the aeration rate. While in the first stage of the SCT process the material is turned twice a day by a proprietary two auger system that mixes and transports the material across the bay in 14 passes over one week. At the end of the stage the augers lift the material over the wall between the first and second stages to ensure mixing of the material between stages to comply with SVS ABPR requirements. This serves as the first barrier in a composting process to comply with SVS ABPR requirements. During the Second ABPR Barrier Treatment of Solids From Percolation the target criterion is once again to achieve a temperature of at least 60°C for two days. In practice once this temperature is achieved it is maintained for the rest of the time as temperature control is achieved by varying the aeration rate. While in the second stage of the SCT process the material is turned twice a day by a proprietary two auger system that mixes and transports the material across the bay in 14 passes over one week. At the end of the stage the augers lift the material onto a conveyor belt that transports it to the third composting / maturation stage. Once the material passes out of the second barrier it has completed the pasteurisation requirements for ABPR compliant composting. At the end of the second barrier the material is sampled for Salmonella and other parameters before moving on to the composting / maturation stage. (In the event of Salmonella being detected in any of the batches of material coming out of the second barrier, that batch of material and the adjacent batched before and after it will have to be removed from the composting / maturation hall for reprocessing or landfill).

The intensive Extended Composting/maturation process converts the crude compost from the two barrier pasteurisation process into a mature compost that exerts negligible phytoxicity. Moisture is added as required during the composting/maturation process to control the moisture content to optimise biological activity during the process and leave it at the optimum level for refining at the end of the process. At the end of this stage, the augers lift the material onto a conveyor belt that transports it to the refining screening section before it moves to on site storage section of the plant.

OGM Refining is where the material is screened and treated by densiometric separation to produce a quality compost product, with low physical contamination. The refined OGM compost can spend up to four weeks in OGM Storage on-site in stockpiles (during which further maturation can occur as there is provision to turn the material weekly).

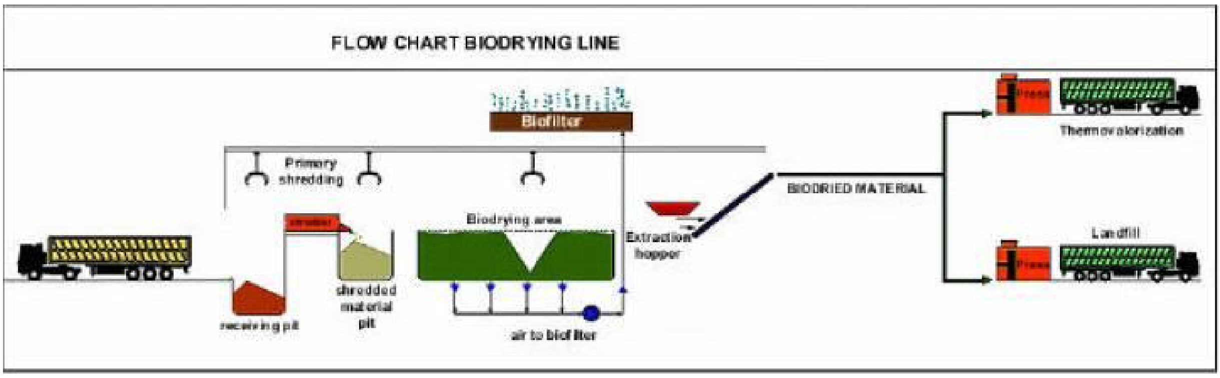

Figure S5. Scheme of the Ecodeco MBT plant.

The entire process is enclosed in a housed building, under a slight negative pressure, to ensure the process performance is optimised and to avoid odour emissions. The building reaches a height of about 12-15 m on a surface of 2,700 m2 for the 60,000 t/y line and 5,400 m2 for the 120,000 t/y line. The total surfaces area, including the area for manoeuvring delivery vehicles, is respectively 9,000 m2 and 15,000 m2.

The Biocubi® treatment consists of the following stages: reception of incoming MSW; shredding of MSW; bio-drying of wastes; mechanical refining; and, treatment of emissions.

Reception of Incoming MSW

After weighing and document checks, the incoming material is unloaded into an underground pit inside the building. The pit has sufficient storage capacity to contain more than 1 day of waste arisings (height of the wastes in the pit is roughly 4.5 m). Programmable bridge cranes (2 for each treatment line of 60,000 t/y), that are completely automated, but can be checked from the control room, carry out all waste handling. They are equipped with grabs (4 m3/each) which operate automatically feeding waste into the shredder.

Shredding of MSW

The shredding is performed during daytime with an operator in the control room who visually checks the unloaded waste and removes any undesirable items, for example any waste which is incompatible or detrimental to the plant's performance (e.g. cylinders, girders, cement blocks, bulky trash, rubble, tyres, etc.). The shredder is a cutting machine, with a slow rotating double shaft placed on a mobile bridge that allows a uniform filling of the shredding pit. The material is crushed to an average size of 20-30 cm. This obtains a homogeneous material in order to facilitate the aeration of the waste to increase the rate of bio-drying/fermentation.

Bio-drying of Wastes

This is a 24 hours process where the crushed and homogeneous material is placed by the bridge crane into the bio-desiccation area to form heaps of up to 6-m high. Since no special controls are required at this stage, this operation may be performed automatically, and at night, without staff supervision. The perforated floor and ductwork system allows process air to be drawn through the waste and transferred to the bio-filters mounted on the roof. Varying the airflow (an operation automatically performed through a computerised control system) makes it possible to exploit the exothermic energy of the process to efficiently bio-dry the waste. Once the biodrying process is complete waste is automatically loaded by the bridge crane into a hopper from where it is sent to the refining section.

Mechanical Refining of Waste

The refining section can be constructed from a number of possible mechanical treatment processes which include: double stage screening (i.e. used to separate the fine heavily polluted materials rich in pollutants (e.g. heavy metals) and mainly non-combustible material and to send the intermediate fraction (dimensions between 2-12 cm) to a separator; iron removal (allows separation of all ferrous materials for recovery); Eddy current separation (enables the separation of aluminium and non-ferrous metals - except stainless steel); aeraulic separation (recovers light particles contained in the intermediate fraction which is then mixed with the upper-sieve fraction after magnetic separation; shredding (i.e. material shredded to make the SF suitable for the designed combustion. Dimension of around 10-15 cm are suitable for fluidised bed combustion installations, dimensions around 3-5 cm for cement factories. The refining and extracting sections are equipped with a devoted aspiration system that channels the air to a de-dusting fabric filter.

Treatment of Emissions

All zones of the plant dedicated to the unloading, storage and treatment of MSW are equipped with aerial treatment systems which is necessary to ensure the correct progress of the Biocubi® process in the bio-drying zone and to avoid the escape of odour.

Air is sucked in by fans located on the roof of the building which, thanks to temperature monitoring sensors on the air inflows, are able to regulate the flowrate and the resulting heat exchange between the stored wastes undergoing the bio-drying process and the air that passes through them. Each fan has a temperature monitoring unit and inverter operation for the control and adjustment of fan speed and therefore flowrate. During processing, the building is always kept in low pressure by the aspiration system. The aspiration plant is able to ensure an internal atmosphere that is normally free of dust and steam and prevents disagreeable odours from escaping outside.

In the bio-drying zone, concrete perforated flooring elements are used, beneath the floor there is an exhaust void from which a series of pipes departs. These pipes channel the air that has passed down through the heaps of waste to the bio-filtration system located on the roof of the building. The bio-filtration process biologically removes the gaseous pollutants, the undesired compounds present in the gaseous phase are temporarily adsorbed on a bed of soft, porous material of plant origin, maintained at adequate humidity, where they are biologically degraded by supported micro-organisms. The process takes place in aerobiosis and the action of the micro-organisms, combined with the admission of oxygen, allows the conversion of the pollutants to carbon dioxide, water, inorganic compounds and bio-mass. The filtering material is a mixture of woody, pulpy material that, due to its structure, porosity, area per unit volume and ability to retain water, is able to provide the best solution for a high value of bio-activity and low resistance to air flow so as to reduce pressure drops and hence installed capacity.

The limited amounts of leachate produced by the plant, (<2% of the weight of the entering MSW), can efficiently be re-circulated and sprayed on the wastes to prolong the stabilisation treatment if considered necessary, or to the FOS maturation zones. If not, the leachate produced is sent to purification plants.

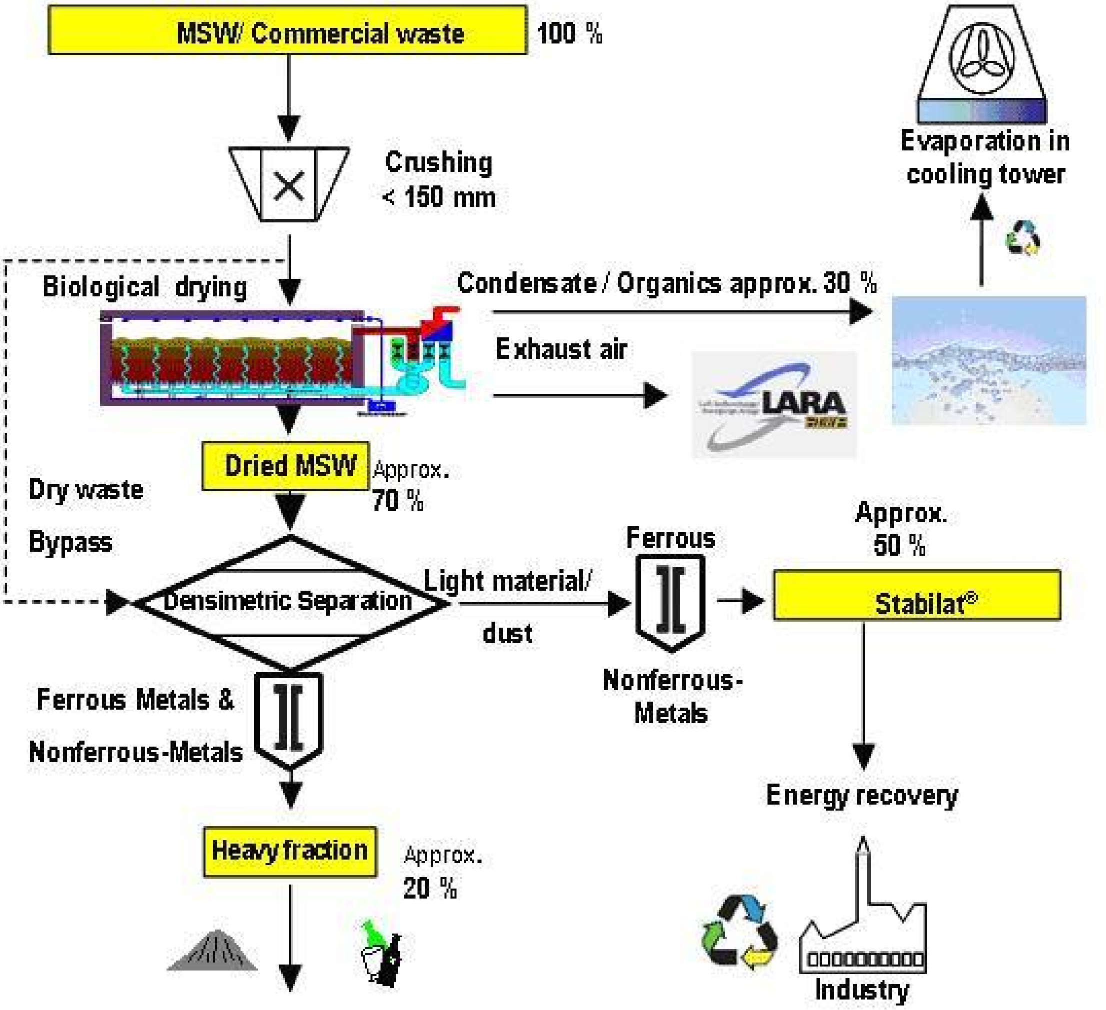

Figure S6. Scheme of the Herhof MBT plant.

The waste treatment plant at Rennerod in Germany is the second waste treatment plant built by Herhof Environmental Technologies, in which the generation of a high-quality fuel from waste is combined with a maximised recovery rate of recyclables. Two other plants with this technology are under construction and a fifth is in the planning stage after the contract has been awarded. On completion of these plants 600,000 tpa of municipal solid waste will be treated with the Herhof new technology.

Summary of the Process

The waste treatment process in this kind of plant can be separated into following steps:

Material preparation in a fully automated system;

Biothermal drying in a semi-composting process;

Separation by means of densimetric tables;

Use of recyclables and fuel;

Material preparation; and

Waste Delivery And Preconditioning (the delivery of the waste is via six automated gates, which act as airlocks. The delivery area is divided into a deep bunker for household waste and a flat area for commercial waste).

An automated delivery crane takes the waste from the deep bunker and feeds it into a shredder, which crushes the material to a particle size of < 150 mm. After the initial separation of ferrous metals, the pre-treated waste is passed to a buffer bunker, where it can be picked up by the process crane serving the biological drying section of the plant.

Filling of the Composting Boxes with the Automatic Crane

The third generation of the Herhof Box System is equipped with an airtight lid system instead of a door at the end of the box. Prior to the top loading of the boxes with the process crane, these lids have to be removed and put on one side. This is done automatically by the crane together with a guide rail system. Then the box is filled homogeneously by the fully automated system and then the lid is replaced to close the box.

Dry Stabilisation process

A six-day aerobic degradation process is started after the composting system box is closed, which is in principle an 'in-vessel composting system' with computer control and forced aeration. However, the process is specifically not designed as a traditional composting process, where the maximum amount of organic material has to be degraded. The target here is to remove as much water from the waste as possible in a short time by generating biothermal energy. This means that the biological heat produced during this process is used to remove the moisture from the material using the air stream. The material to be biodegraded is mainly easily degradable organic matter, which is the reactive part in the organic fraction. The water is removed from the airstream by means of a heat exchanger system and is subsequently cleaned in a water treatment unit.

The main reasons for drying the waste are as follows: dry waste (< 15% moisture), with a minimised content of reactive organics, is stable; only dry waste can be effectively separated into the different fractions of recyclable materials; and, historically all attempts to separate wet waste have not achieved adequate results.

Air and Water Cleaning, Occupational Health

Important features of a waste treatment plant are neither to pollute the air or the water nor to create hazardous conditions inside the plant, which could have negative effects on the workers. Hence, in Rennerod great emphasis was put into improvement of these aspects of the plant.

Cleaning of the Exhaust Air

The biological treatment of municipal solid waste generates an exhaust air rich in total organic carbon along with a lot of chemical compounds, which cannot be removed with a simple biofilter. Hence, in Rennerod a special combustion process is used for the effective cleaning of the waste air. The process was developed by Herhof and it is the first time that a system like this has been used in a biological waste treatment plant. The combination of the minimised, concentrated exhaust air delivered by the Herhof boxes and the so-called thermal regenerative cleaning unit gives results that not only meet the demands of state-of-the-art air treatment, but also achieve running costs comparable to those of conventional systems.

Wastewater Treatment

The moisture or condensate that is removed from the waste with the heat exchanger is cleaned in a special water treatment plant. This is a two-stage cleaning plant, consisting of a high-performance biological phase combined with a downstream ultrafiltration stage. The cleaned water is used internally for cooling purposes and can be considered as the first recycled product. Using this process, the Rennerod installation does not generate any wastewater.

Occupational Health

The plant in Rennerod is optimised in such a way that employees do not have contact with the waste. All waste-processing parts of the plant are enclosed and air is extracted at every point of emission in order to minimise plant internal emissions that could affect the workers. Almost complete automation reduces the number of workplaces to a minimum and these are in safe areas. We can therefore operate in compliance with the toughest European health and safety at work requirements.

Creating Fuel from Waste

Drying reduces the mass of the waste by 30%, increases its calorific value and makes it stable against further decomposition. The different materials are separated out during the downstream process. The dry condition of the material (in Rennerod 12% moisture content is achieved in full operation) is an important prerequisite for the efficiency of these separation steps and the quality of the different separated fractions. The separation is done by so-called densimetric tables, which separate heavy from light materials according to their specific weight.

The dry, lightweight material, which is separated from the rest, is the so-called stabilate [Trockenstabilat(r)]. This consists of almost 100 % combustible constituents, such as wood, paper, plastics, textiles and organic materials. The percentage of regenerative energy carriers, such as paper, cardboard, wood and organic textiles, which enable CO_2-neutral energy generation, is around 65 %. The calorific value of the stabilate is in a range of 15 to 18 MJ/kg and therefore represents an energy equivalent to processed and dried lignite coal. The proportion of dust separated out throughout the process stage by fibrous filters is approximately 1% of the inert fraction. This is formed into pellets and added to the stabilate. Because of its dry and stable consistency, stabilate can be very easily stored and transported and therefore used as a secondary fuel in industrial processes.

The separation of metal parts, and therefore of contaminants like batteries, is of critical importance for the use of stabilate. The heavy-metal content is reduced by up to 90% compared to residual waste. In consequence, stabilate is not only a high calorific fuel but also a fuel almost completely free of contaminants and thus can be compared to traditional fossil fuels like coal.

Extraction and Use of Recyclables

Prior to the recycling of the heavy materials, they are subjected to additional treatment stages (however, these do not take place at Rennerod, but in the Asslar plant, where the capacity has been extended for this purpose).

The heavy fraction is first processed through a ferrous metal (magnet) separator and then through a non-ferrous metal (eddy current) separator. The separated metal fractions are sold to recycling companies, which helps to reduce the overall net costs of the process. The remaining material, which now mainly consists of ceramics, stones, porcelain and glass fragments, goes through a glass separation unit of a type that has been tried and tested for years in the treatment of separately collected waste glass.

The separation of the glass fractions, here carried out for the first time in a residual waste treatment plant, contributes to a noticeable increase in the proportion of material recycled and, at the same time, opens up new possibilities for cost-efficient used-glass collection and reuse. The quality of the remaining mineral fraction - approximately 35% - complies with the requirements for use in road construction and is recycled accordingly.

Use Of the Stabilate Fuel

The Stabilate produced in the Rennerod plant is either used in the German Cement Industry or at the SVZ (Schwarze Pumpe), a company where methanol is produced under compliance with the German emission act. It replaces the primary energy supply in both processes and, as a result of the high proportion of renewable energy sources in the Stabilate, a contribution is also made to global CO_2 reduction.

In addition, Herhof is focusing its research on modern gasification and degasifying processes, in which Stabilate can be economically used in the thermal process without any additional treatment steps. Initial trials have confirmed the technical feasibility of the approach. Because of its good storage properties, the Stabilate fuel can be used for specific energy supply, independently of the amount, timing and location of the generated waste. For the first time ever in the waste industry, decentralised, flexible energy supply concepts that are tailor-made to suit the actual energy requirements are possible. This is the basis for an increasingly urgent correlation between the objectives of the waste and energy industries.

The metals and the glass fraction are recycled, the mineral fraction is reused as a construction material. This and the reuse of process water, plus the use of stabilate in industry, makes it possible to achieve 100% recycling and eliminate the need for landfill for the processed waste.

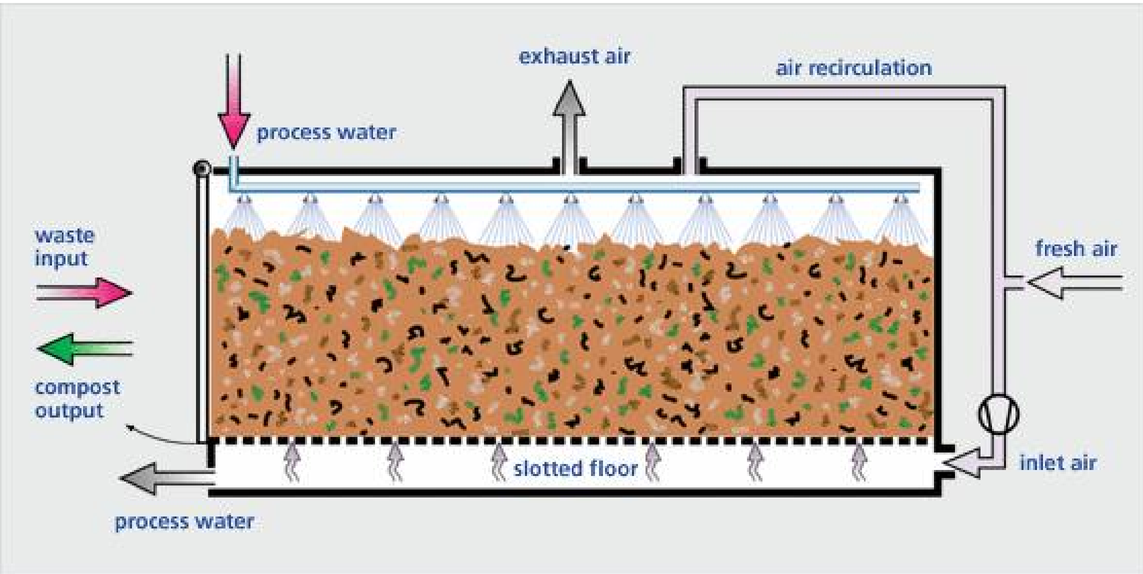

Figure S7. Scheme of the Linde MBT plant.

The MBT plant at Linz is designed for 65.000 tons per year, although it typically operates at approximately 75.000 tonnes per annum, and can be enlarged up to 85.000 tons when required.

All the delivered waste is registered by the weighbridge at the MBA. The waste is discharged in the delivery area. Oversize components are separated in the delivery area and disposed of to landfill.

A front end loader loads waste into the plant. Mechanical separation takes place in two lines, where the waste is shredded and then subjected to metal extraction using overband magnets. The material is then fed to a screening drum (trommel) where the high caloric material is separated for further usage.

The smaller material from the trommel is conveyed to the 16 composting tunnels. The material is composted for 4 weeks in the tunnels and then the biological treated material is screened. The middle caloric material is separated for further use/combustion.

The smaller material is transported to the deposit area (landfill) where a further biological treatment of approx. 8 to 10 weeks will be carried out in open windows to reach the parameter of the Austrian landfill deposite regulations. The off gases from the tunnels are washed by acid scrubbers and then passed through bio-filters before emission to the atmosphere. The off-gas from the delivery area and take over stations is also passed thorough a bio-filter.

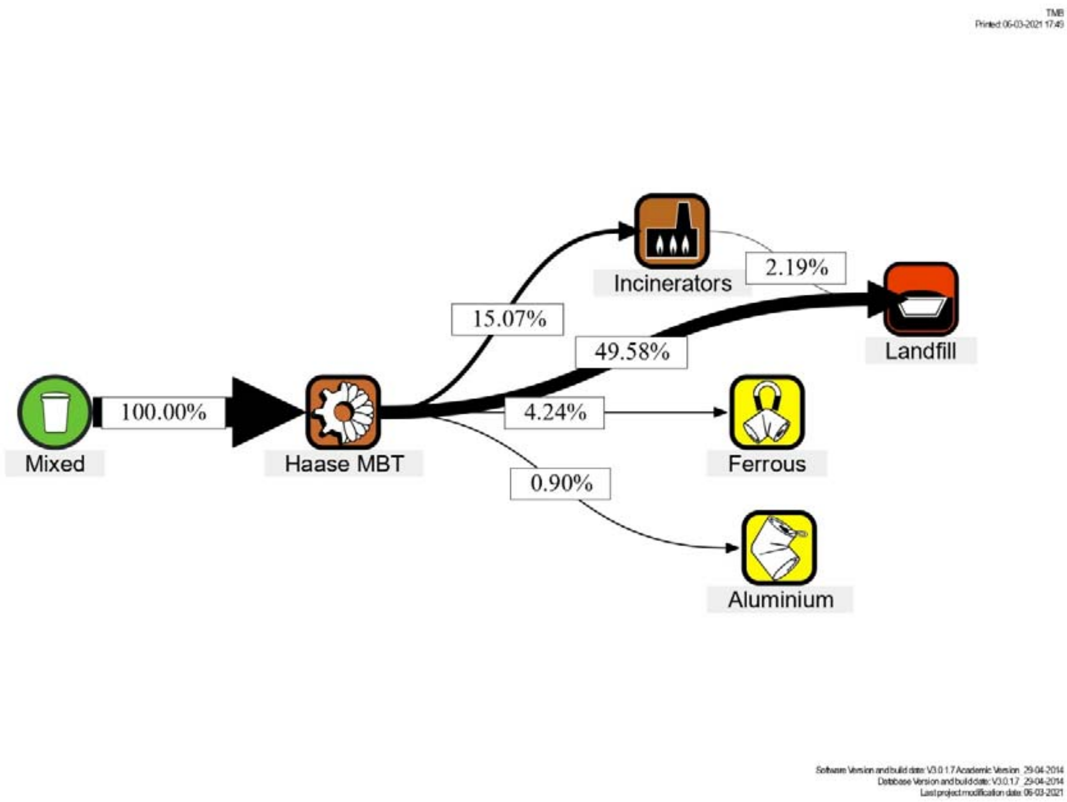

Figure S8. MFA result in Sankey diagrams of Haase MBT plant.

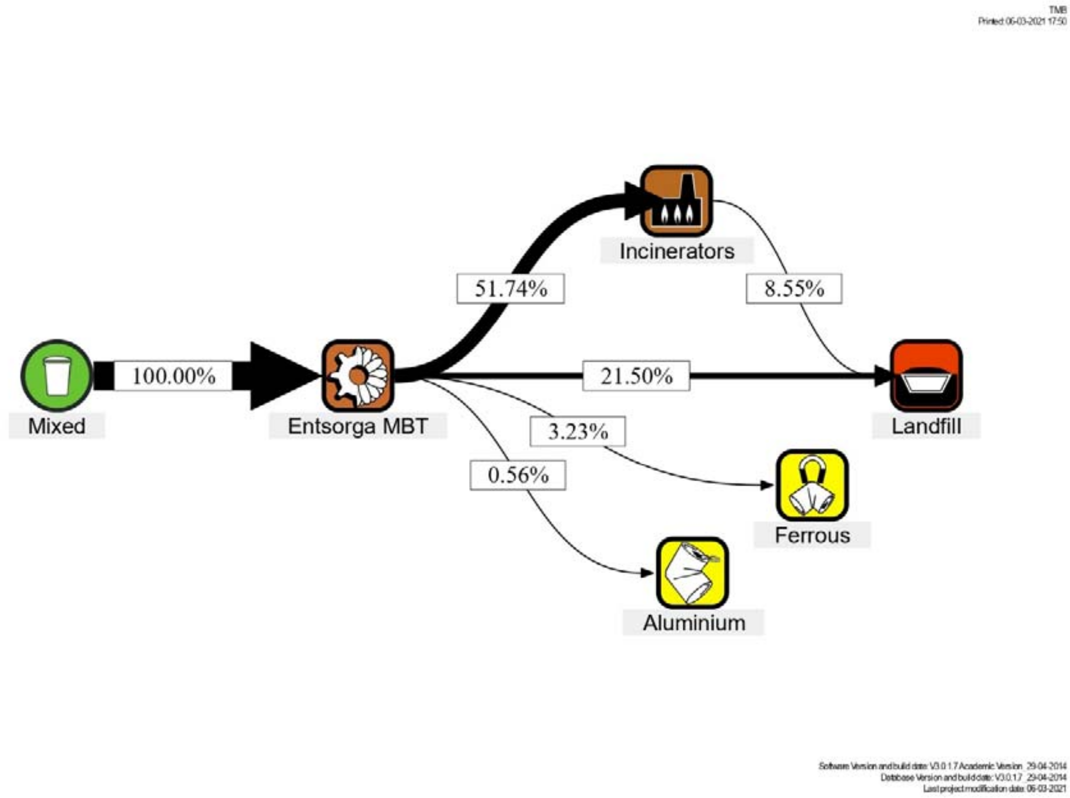

Figure S9. MFA result in Sankey diagrams of Entsorga MBT plant.

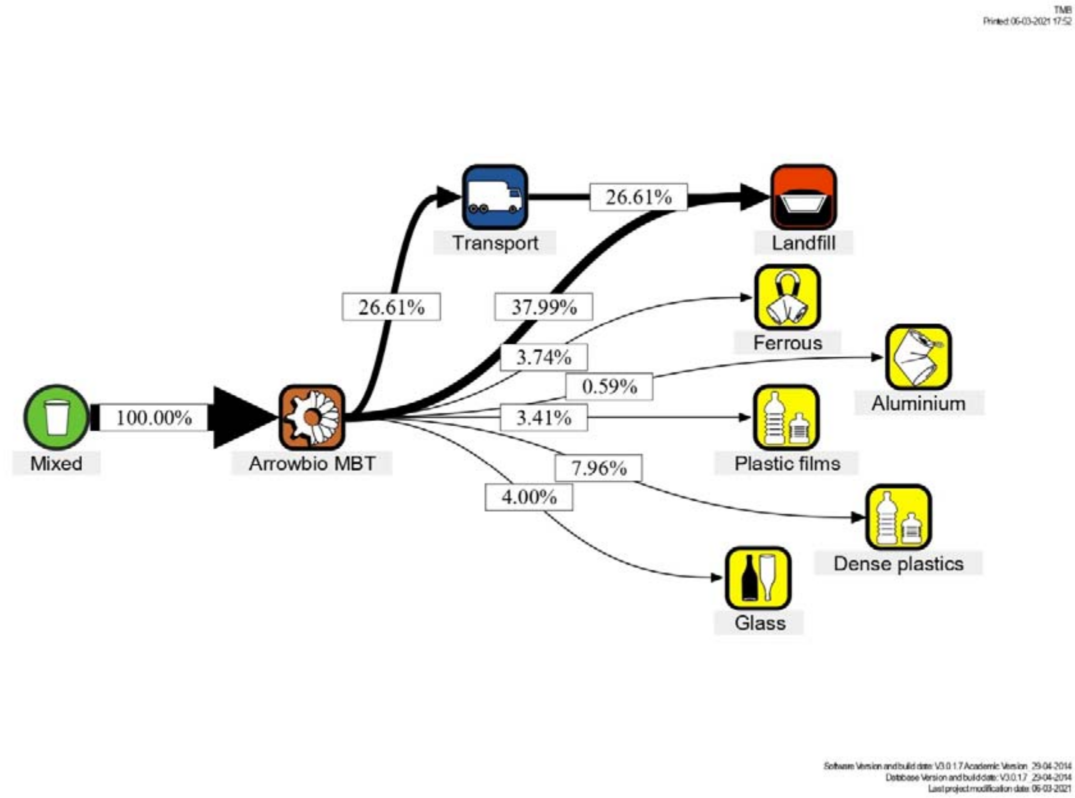

Figure S10. MFA result in Sankey diagrams of ArrowBio MBT plant.

The transportation stage in this scenario was fictitious. It was necessary for the non-compatibility of WRATE [24] to send product and waste from a process to the same operation (in this case landfill). Hence, transportation was modelled for the negligible length of 0.1 km.

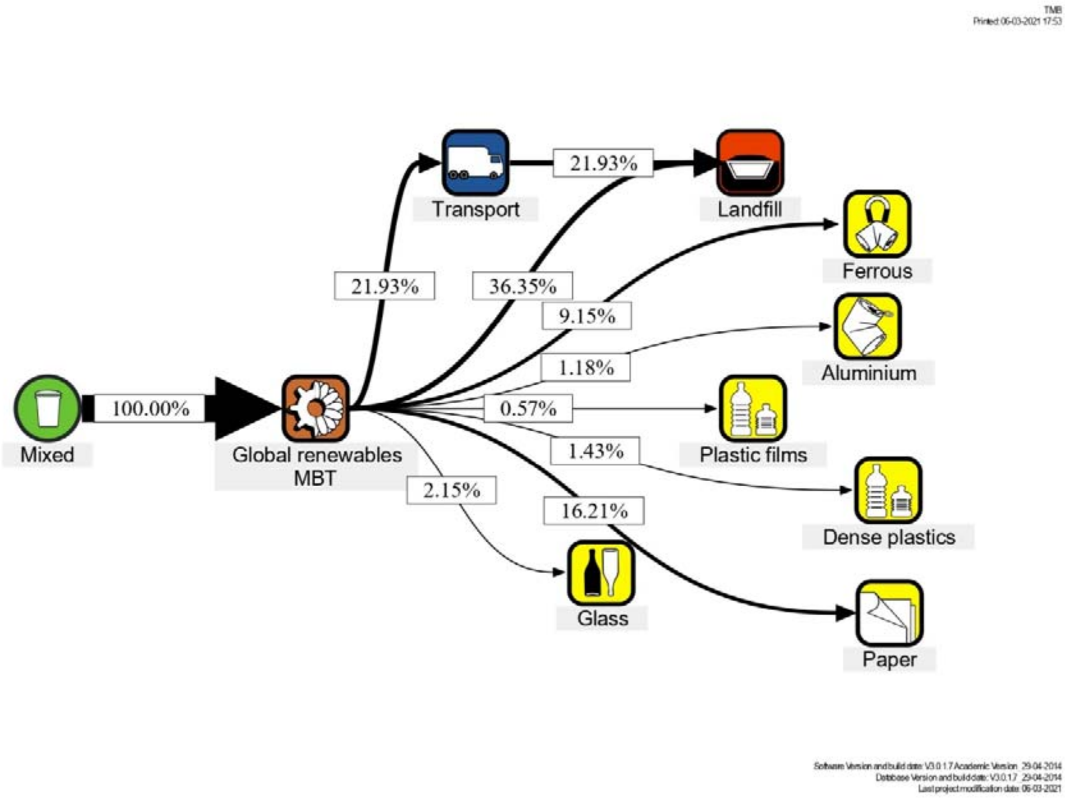

Figure S11. MFA result in Sankey diagrams of Global Renewables MBT plant.

The transportation stage in this scenario was fictitious. It was necessary for the non-compatibility of WRATE [24] to send product and waste from a process to the same operation (in this case landfill). Hence, transportation was modelled for the negligible length of 0.1 km.

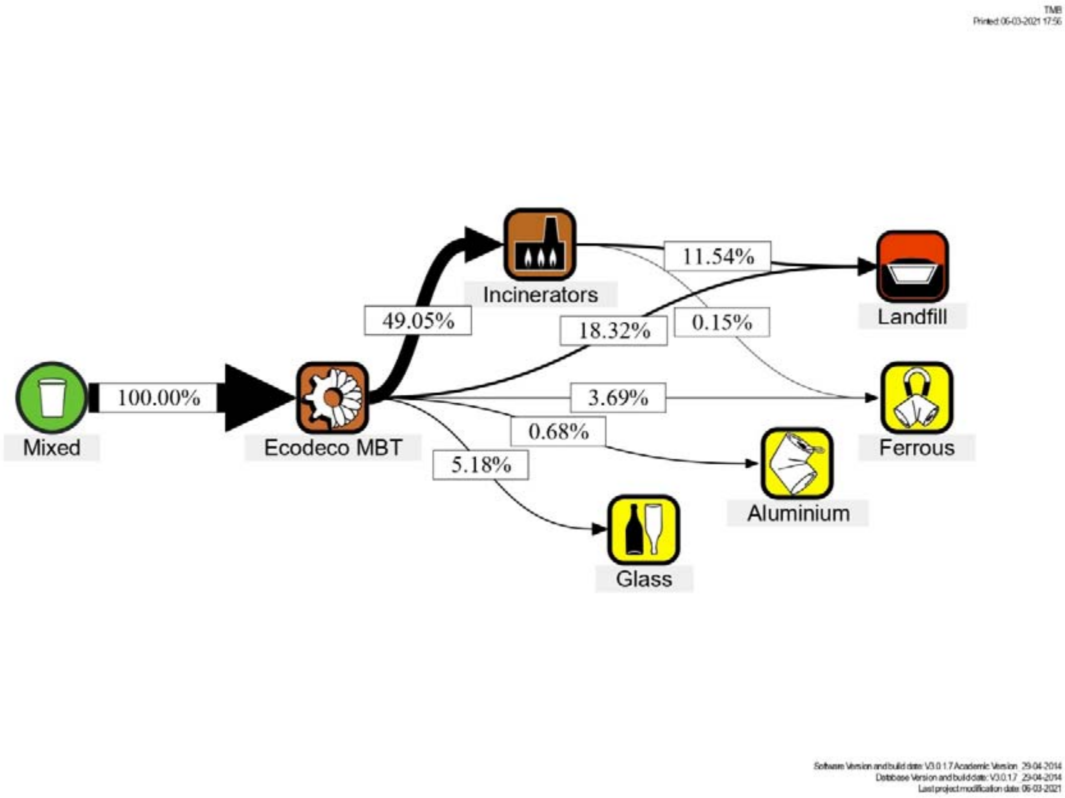

Figure S12. MFA result in Sankey diagrams of Ecodeco MBT plant.

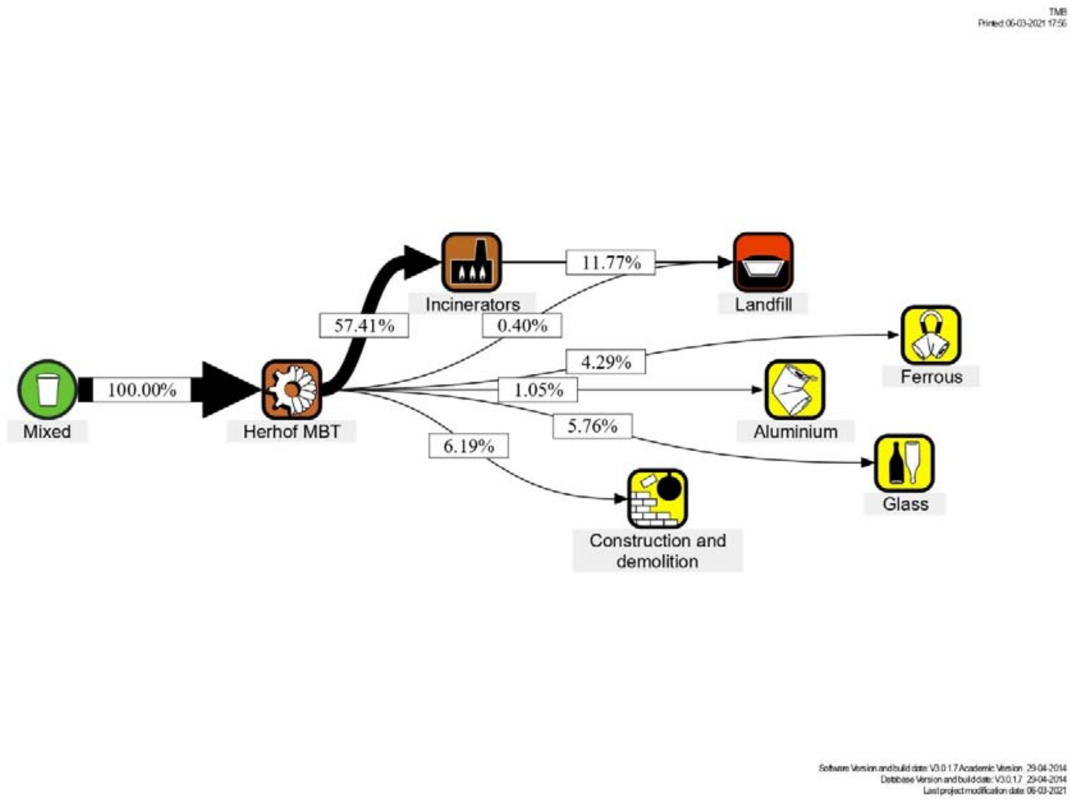

Figure S13. MFA result in Sankey diagrams of Herhof MBT plant.

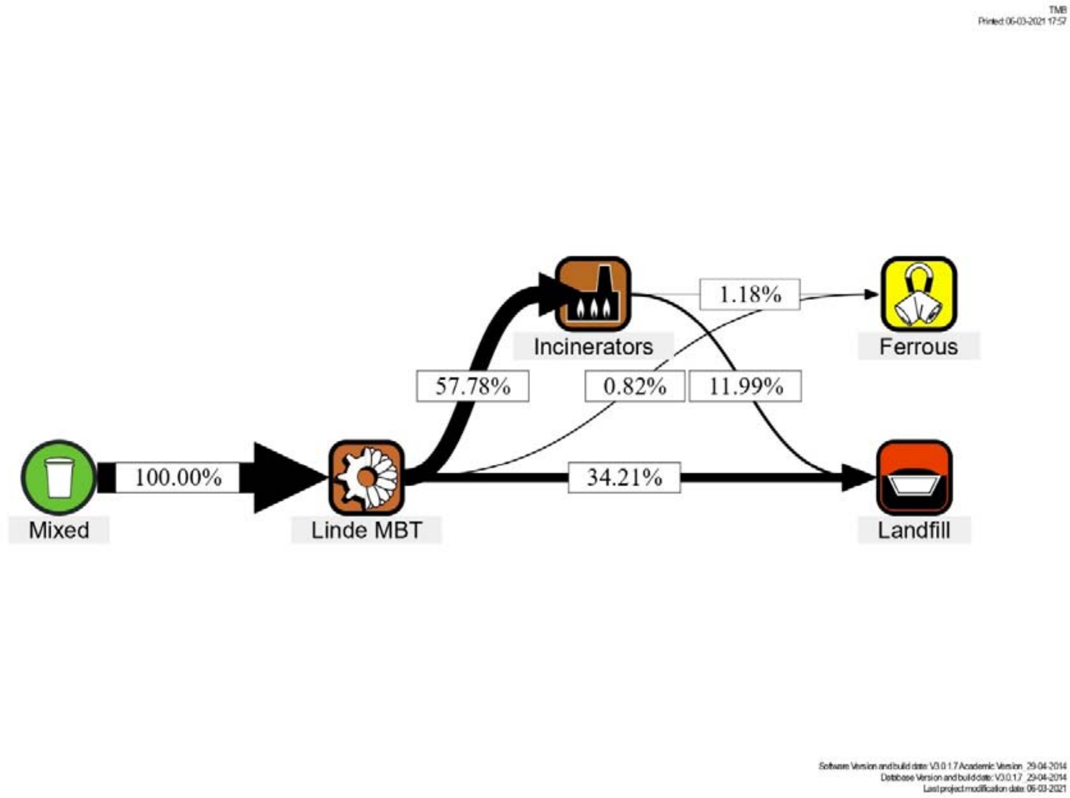

Figure S14. MFA result in Sankey diagrams of Linde MBT plant.

Table S2. LCIA characterization results

Plant	Glob Warm	Acid Rain	Eutroph'n	Aqua Ecotox	Health	Resources
	kg CO_2-Eq	kg SO_2-Eq	kg PO_4-Eq	kg 1,4-DCB-Eq	kg 1,4-DCB-Eq	kg Sb-Eq
MBT process						
Haase	-31.9	-0.0283	0.0619	0.335	32.5	-0.748
Entsorga	20.2	0.0433	0.00784	1.12	35.6	0.131
ArrowBio	-223	-0.344	-0.0248	-2.59	42	-1.77
Global Ren.	40.5	0.314	0.0298	6.36	90.1	3.57
Ecodeco	25.8	0.0534	0.0285	1.36	52.6	0.159
Herhof	39.9	0.0756	0.0114	2.53	49.6	0.344
Linde	-19.2	-0.279	-0.0392	-5.76	60.4	-0.0652
Landfill						
Haase	108	-0.0623	0.172	-0.314	-3.21	-0.589
Entsorga	16.7	-0.0025	0.0391	2.19	3.96	-0.0746
ArrowBio	119.855	-0.0565	0.243762	0.1373	-4.055	-0.63479
Global Ren.	95.555	-0.0438	0.175762	0.2983	-2.975	-0.49779
Ecodeco	39	-0.0225	0.0427	2.43	3.54	-0.205

Herhof	0.348	0.00216	0.00166	2.29	5.32	0.00654
Linde	42	-0.0153	0.108	2.67	4.05	-0.209
Recycling						
Haase	-165	-0.7	-0.0661	-45.5	-527	-1.18
Entsorga	-112	-0.47	-0.0446	-28.5	-330	-0.826
ArrowBio	-213	-0.876	-0.0349	-30.7	-352	-2.84
Global Ren.	-340	-1.54	-0.133	-58.9	-725	-2.85
Ecodeco	-136	-0.572	-0.0547	-34.7	-401	-1.01
Herhof	-185	-0.793	-0.075	-53.4	-618	-1.31
Linde	-32.6	-0.117	-0.0118	-0.861	-9.7	-0.305
Incineration						
Haase	2.55	-0.0717	0.0138	-2.13	-12.8	-1.11
Entsorga	-93.5	-0.227	0.0499	-7	-42.4	-3.66
ArrowBio	0	0	0	0	0	0
Global Ren.	0	0	0	0	0	0
Ecodeco	-41.5	-0.129	0.0547	-5.76	-33.6	-3.07
Herhof	-86.2	-0.22	0.0577	-7.49	-44.4	-3.94
Linde	-73.2	-0.0614	0.0752	-5.45	-30.3	-3.02
All processes						
Haase	-86.2	-0.862	0.182	-47.6	-510	-3.63
Entsorga	-169	-0.656	0.0522	-32.2	-333	-4.43
ArrowBio	-316	-1.28	0.184	-33.1	-314	-5.25
Global Ren.	-204	-1.26	0.0725	-52.3	-637	0.225
Ecodeco	-113	-0.671	0.0712	-36.7	-379	-4.12
Herhof	-231	-0.935	-0.00426	-56.1	-608	-4.9
Linde	-82.9	-0.473	0.132	-9.4	24.4	-3.6

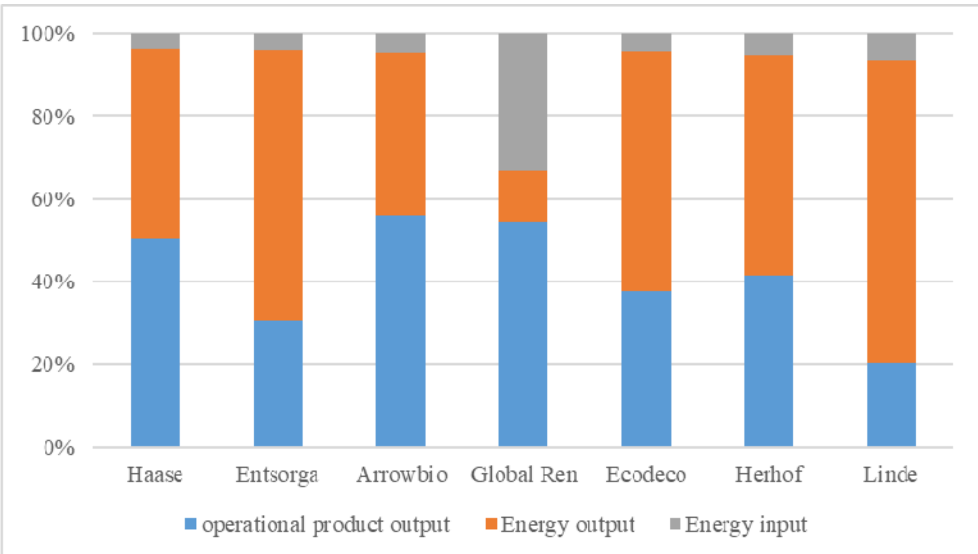

Figure S15. Contribution of operational product output, energy output and energy input on the LCIA results for each MBT plant.

References

[24] Golder. WRATE Download Version 4. 2017. Available online: http://www.wrate.co.uk/Page/Download (accessed on 5 April 2022).

[30] Hischier, R.; Weidema, B.; Althaus, H.-J.; Bauer, C.; Doka, G.; Dones, R.; Frischknecht, R.; Hellweg, S.; Humbert, S.; Jungbluth, N.; et al. *Implementation of Life Cycle Impact Assessment Methods*; Data v2.2 2010; Ecoinvent Report No. 3; 2010. Availible online: https://docplayer.net/14249358-Implementation-of-life-cycle-impact-assessment-methods.html (accessed on 10 May 2022).